NASA/CR—2000-210694

Detection, Tracking and Analysis of Turbulent Spots and Other Coherent Structures in Unsteady Transition

Jacques Lewalle
Syracuse University, Syracuse, New York

December 2000

The NASA STI Program Office . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the Lead Center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA's counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.
- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.
- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.
- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.
- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.
- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized data bases, organizing and publishing research results . . . even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at ***http://www.sti.nasa.gov***
- E-mail your question via the Internet to help@sti.nasa.gov
- Fax your question to the NASA Access Help Desk at 301–621–0134
- Telephone the NASA Access Help Desk at 301–621–0390
- Write to:
NASA Access Help Desk
NASA Center for AeroSpace Information
7121 Standard Drive
Hanover, MD 21076

NASA/CR—2000-210694

Detection, Tracking and Analysis of Turbulent Spots and Other Coherent Structures in Unsteady Transition

Jacques Lewalle
Syracuse University, Syracuse, New York

Prepared under Contract C–76220–D

National Aeronautics and
Space Administration

Glenn Research Center

December 2000

Acknowledgments

This work was performed by Wavelet Diagnostics Ltd. under NASA GRC Contract C–76220–D, Dr. David Ashpis, project monitor. Data were provided by Dr. David Halstead, General Electric Aircraft Engines, Evandale, Ohio.

Available from

NASA Center for Aerospace Information
7121 Standard Drive
Hanover, MD 21076
Price Code: A03

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22100
Price Code: A03

Available electronically at http://gltrs.grc.nasa.gov/GLTRS

Detection, tracking and analysis of turbulent spots and other coherent structures in unsteady transition

Jacques Lewalle
Department of Mechanical, Aerospace
and Manufacturing Engineering
Syracuse University
Syracuse, NY 13244

Abstract

Transition on turbine blades is an important factor in the determination of eventual flow separation and engine performance. The phenomenon is strongly affected by unsteady flow conditions (wake passing). It is likely that some physics of unsteadiness should be included in advanced models, but it is unclear which properties would best embody this information. In this paper, we use a GEAE experimental database in unsteady transition to test some tools of spot identification, tracking and characterization. In this preliminary study, we identify some parameters that appear to be insensitive to wake passing effects, such as convection speed, and others more likely to require unsteady modeling. The main findings are that wavelet duration can be used as a measure of spot size, and that spot energy density is most closely correlated to the wake passing. The energy density is also correlated to spot size, but spot size appears unrelated to the phase angle. Recommendations are made for further study.

1 Introduction

The purpose of this report is to show to what extent wavelet-based methods can assign quantitative properties to coherent structures (spots and possibly others) occuring in turbomachinery. Specifically, we study traces collected at the wall in a boundary layer experiencing unsteady transition in relation with wake passings. The data used in this report is from experiments performed at General Electric Aircraft Engines (GEAE) in their low speed research turbine facility. The experiment is documented in Halstead [5] and Haltead et al. [6], where the experimental configuration and data acquisistion are described in detail. The data include free stream hot wire and surface hot film measurements in a two stage turbine.

In the companion report [11], we focussed on the hot wire records taken upstream of the first and the second turbine nozzles. In this report, we follow up with an analysis of the hot film traces collected on the second stage nozzle. Under the effect of wake passing from the first turbine stage, unsteady transition occurs [5, 6]. This part of the study is devoted to the characterization of recognizable events (turbulent spots and other phenomena) associated with the wake-induced transition.

The motivation for this analysis comes from the need to model wake-induced transition and unsteady separation that may occur in low-pressure turbines. The GEAE data [6] show vividly the dependence of spot formation on wake passing, the subsequent delay in further spot formation in the becalmed region, the effect of these phenomena on separation, and the need for unsteady model predictions that take spot dynamics into account. The explicit goal of this preliminary study was to evaluate which spot properties can be quantified based on hot film data, and which seem to be affected by unsteadiness. Whether positive or negative, the outcome would be of interest: insensitivity to unsteadiness would make conventional transition models satisfactory, while some effect of unsteadiness may have to be included to improve model predictions. The fact that the current data was not collected specifically for this purpose set certain limitations on expected results, but allowed for the evaluation of methods and software, and some preliminary conclusions are drawn.

The hot film records consisted of a collection of 400 samples of 700 data points each (the first 512 of which are used in our analysis) at 24 chordwise locations on the suction surface of the second stage vane. The amplitude of the signals is a measure of pseudo-wall-shear-stress (PWSS), which can be interpreted as the footprint of velocity fluctuations in the boundary layer. The relation between maps of the instantaneous velocity field and the wall heat transfer was established by Van Atta & Helland [13], and can also provide a high-frequency-response non-intrusive access to the transitioning boundary layers in high speed flows [8, 2].

Preprocessing of the GEAE data yielded an ensemble average at each station, which provides smooth data to measure the phase relative to the first stage blade passing; and fluctuations around this ensemble mean, from which we endeavored to extract individual events. The availability of simultaneous traces at 24 chordwise stations along the vane provides an opportunity to document the evolution of spot size, time scales, energy levels, convection speed, etc., as a function of phase relative to the wake passing. The motivation for this focus is to determine which spot properties are affected by the variations in freestream conditions. The answer to this question would affect the demands on computational models of transition on turbine blades.

This report is in three parts. Section 2 will focus on spot detection and tracking along the chord. This work differs from conventional methods by the identification and matching of possible events in the time-frequency domain, which allows for the superposition of events of different sizes. In Section 3, event properties and their evolution are mapped. The results are discussed in Section 4, where suggestions are made for future work.

2 Spot detection and tracking

Turbulent spots and their distinguishing characteristics are well documented, e.g. [13]. However, their appearance is strongly affected by the unsteady mean flow, the ambient turbulence, and the frequency resolution of the hot-film sensors. Throughout this report, 'spot' is used as a generic term for an energetic turbulent event that can be followed from station to station. From the physics of the flow, it is clear that some of these events are indeed associated with spots. The frequency resolution of the data does not allow us to determine unambiguously if the event's internal structure is consistent with a spot or not, and it is possible that some events are fluctuations in PWSS other than spots. Further study based on higher frequency resolution data may lead to refinements in this regard.

In this work, spot detection is a three-step process. In the first step, candidate events are located in each trace separately, as explained in Subsection 2.1. Visual inspection of the traces and wavelet maps showed that the properties of small spots superposed on energetic large-scale events were modified by these dominant events, and the successful removal of the large events in the time-frequency domain, described in Subsection 2.2, yielded more accurate event properties. If events can be tracked reliably at several chordwise locations, they are retained as 'coherent structures' or 'spots', whereas untrackable events are discarded. The tracking algorithm is described in Subsection 2.3. In Section 3, the analysis of spot properties and their evolution is based on the remainder of the collection.

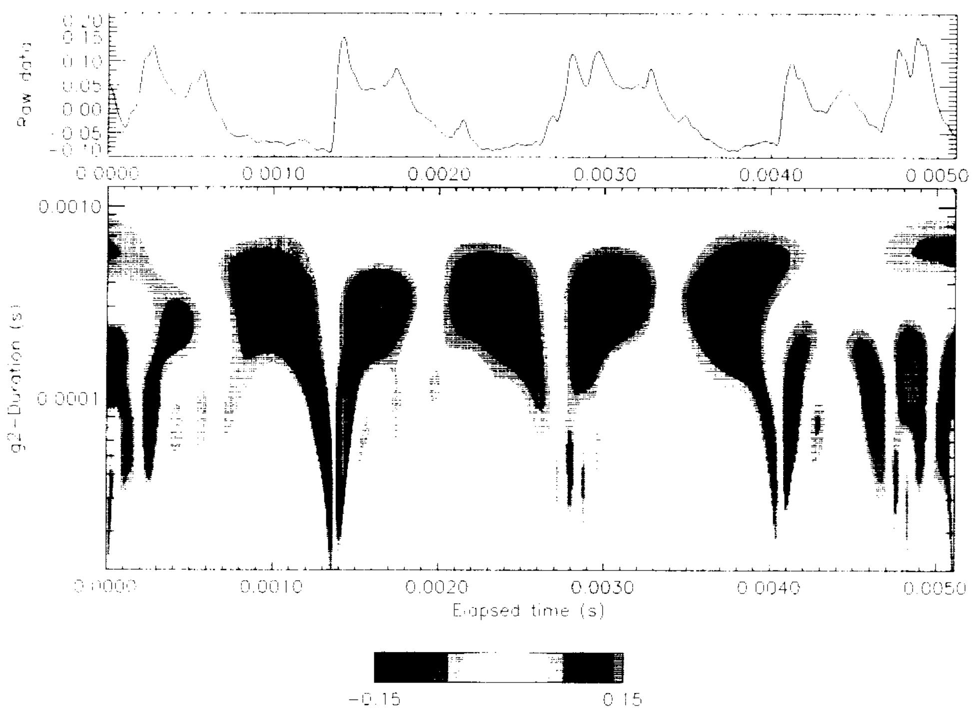

Figure 1: *Trace of pseudo-wall-shear-stress (PWSS) at the beginning of transition (station 12 of the GEAE data), and Mexican hat wavelet transform.*

2.1 Event detection

Traditional methods of spot detection (Hedley & Keffer [7]; Lewalle, Ashpis & Sohn [10]) are based on the presence of smaller scale turbulence in the spot than outside. Because of the frequency resolution of the hot film sensors, such algorithms could not be used with this data. Instead, we relied on the increased PWSS associated with the turbulent transport in each spot. We recorded as candidate event any point at which the PWSS is maximum[1]. Such maxima are readily observable on the traces (see Fig. 1, top.)

A description of recognizable events should include their time of occurence, magnitude and scale, shape, internal structure and eventually dynamics. The first three of these factors point to wavelet analysis [3, 4, 9, 10], and we focussed on the characterization of the events in the time-frequency domain [4, 9]. Wavelets have imposed themselves as a rigorous tool for time-frequency analysis, with solid mathematical

[1]Alternative criteria, based e.g. on local curvature of the traces, were attempted but were not sufficiently sensitive to large events and excessively sensitive to noise.

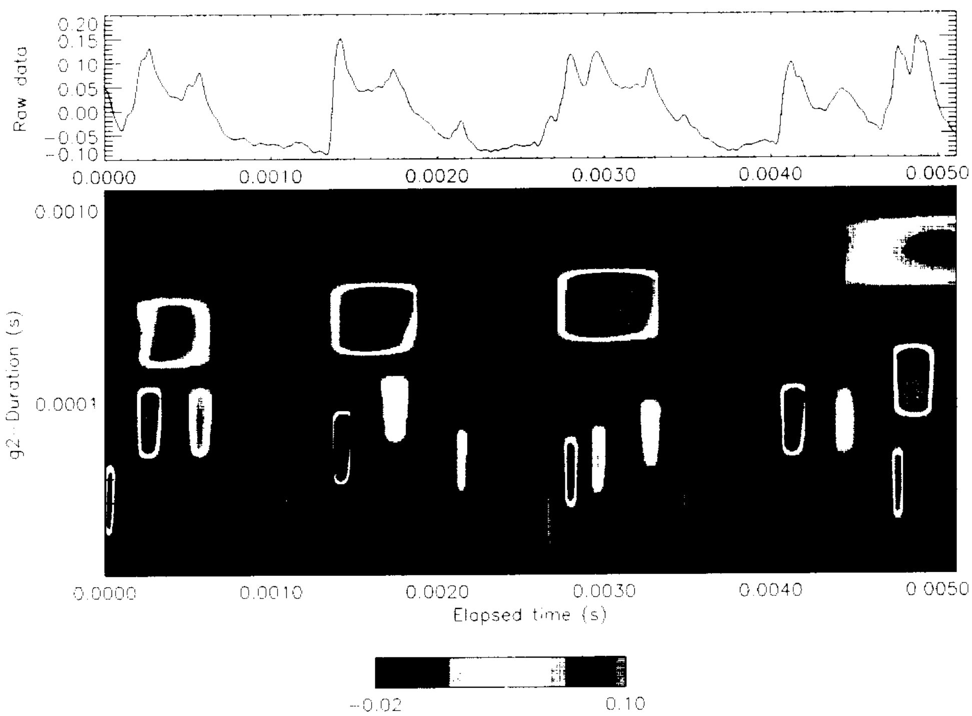

Figure 2: *Local maxima of energy density isolate the 'events' to be studied. The same sample as on Fig. 1 is shown.*

underpinnings for the wavelet transform, its inverse (with or without filtering), and the generalization of power spectral density to intermittent signals. Contour lines of the wavelet coefficients, multiplied by the square root of scale ($\sqrt{k}$) to enhance dominant events at all scales, are shown on Fig. 1, bottom. The square of the coefficients measure the energy density per octave according to Parseval's theorem [3]. A good correspondence between the local maxima of this energy map and local maxima of the signal can be observed on Fig. 2. (For the algorithm of extrema identification, see Lewalle, Ashpis & Sohn [10]). The location of the local maximum of energy in the wavelet domain provides the time of occurence and scale of of the event, while the peak energy level is a local measure of the magnitude.

A correction to this idea was required due to an observation related to the imperfect time/frequency localization of the events (a manifestation of Heisenberg's uncertainty principle in the wavelet plane). With the Mexican hat wavelet, temporal localization is favored [9], resulting in fairly long spectral tails for each bump as seen on Fig. 1. In the case when the small events (0.1 ms duration and less) overlaps in time with a large scale event (which is associated with a wake passing as a matter of course), the coefficients associated with the peak of the weaker event are superposed on the tail of the stronger event. This affects both the peak frequency and the magnitude of the smaller event, an undesirable contamination from the viewpoint of our analysis. Thus, we turned to intermittent filtering to improve the accuracy.

2.2 Removal of large events

In a first attempt, a conventional high-pass filtering was attempted to remove the large scale events. In the Fourier domain, this strategy failed because the wake-passing events are not sinusoidal, even though they are nearly periodic. The higher-frequency corrections that account for their average shape turned out to interfere more with the desired event characterization than the original peaks. In the wavelet domain, frequency filtering obviously leaves unchanged the higher-frequency contamination. What is needed is a method to remove the dominant bumps and their higher-frequency tails.

Let us call t the time variable on the experimental traces, and $u(t)$ the signal; κ is the wavelet number [10] playing a role similar to the frequency of Fourier analysis, and g_2 is the Mexican hat wavelet function

$$g_2(t) = \frac{d^2}{dt^2} e^{-t^2/2}. \tag{1}$$

The large event removal algorithm devised in this study is based on the inverse wavelet transform formula:

$$u(t) = \int_0^\infty \kappa^{1/2} \int_{-\infty}^\infty g_2(\kappa(t-\tau))\; u_2(\kappa,\tau)\; d\tau\; d\kappa \tag{2}$$

Integrations by parts and the definition of the Gaussian bell curve

$$g_0(t) = e^{-t^2/2} \tag{3}$$

give

$$\begin{aligned} u(t) &= \int_0^\infty \kappa^{-\frac{3}{2}} \int_{-\infty}^\infty g_0(\kappa(t-\tau))\; \tfrac{\partial^2}{\partial \tau^2} u_2(\kappa,\tau)\; d\tau\; d\kappa \\ &= \int_{-\infty}^\infty d\tau \int_0^\infty \tfrac{d\kappa}{\kappa} g_0(\kappa(t-\tau))\; [\kappa^{-\frac{1}{2}} \tfrac{\partial^2}{\partial \tau^2} u_2(\kappa,\tau)] \\ &\sim \textstyle\sum_i a_i g_0(\kappa_i(t-\tau_i)) \end{aligned} \tag{4}$$

This equation shows that the signal can be decomposed into a superposition of Gaussian bell-shaped curves $g_0(\kappa(t-\tau))$ over the continuum of times and scales. The dominant contributions to the signal will be those associated with the times and scales where $\kappa^{-\frac{1}{2}}\frac{\partial^2}{\partial\tau^2}u_2(\kappa,\tau)$ is largest. It has been shown (Lewalle, unpublished) that a multipole expansion around the extrema gives a discretized Gaussian bump as the leading term.

Thus, a first order approximation of the wake-passing bump consists of the Gaussian bell at the time and scale of each bump. The event removal algorithm is therefore summarized as follows:

1. Identify the location and scale of the wake-passing events from the large-scale maxima of the energy map Fig. 2;
2. Calculate the magnitude of the Gaussian model so that its energy peak coincides with the wake passing energy signature;
3. Construct the model Gaussian bump with these parameters;
4. Subtract the model bump from the signal and from its wavelet transform.

A more extensive discussion of the Gaussian model for wake passing events will be found in Section 4. The result of the procedure is shown on Figs. 3 and 4. One-by-one mapping of the original maxima of the raw signal (the candidate events) was found to be satisfactory; hardly any original events were lost in the procedure, thanks to the scale separation, and new events introduced as a result of the subtraction of model Gaussians were *not included* in the list. In other words, the events analyzed below were always identified on the original traces, without exception. The map of wavelet coeffficients (Fig. 3) shows that the tail of the bumps has effectively been removed, and the modified energy peaks (compare Figs. 2 and 4) are deemed to provide a valid correction to the contaminated parameters obtained previously. Events were retained if we could match the local maximum of the raw trace to a local energy peak in the filtered energy map.

2.3 Spot tracking

Up to this point, the list of events and their properties are calculated for each trace independently. The last step in the procedure consists in matching them at successive stations. The occurence of 'similar' events with some time delay on the next trace is the basis for a match. The time delay is first estimated from the peak of the cross correlation function for the two traces [1]; The events are paired up based on a positive convection speed and the 'best' overall matching of time, scale and magnitude. Since a given event can find a suitable match only in very small region of the time-frequency domain at the next station, the automated pairing procedure was relatively easy even if time-consuming. All unmatched events were deleted from the list of candidates. The result is shown on Fig. 5.

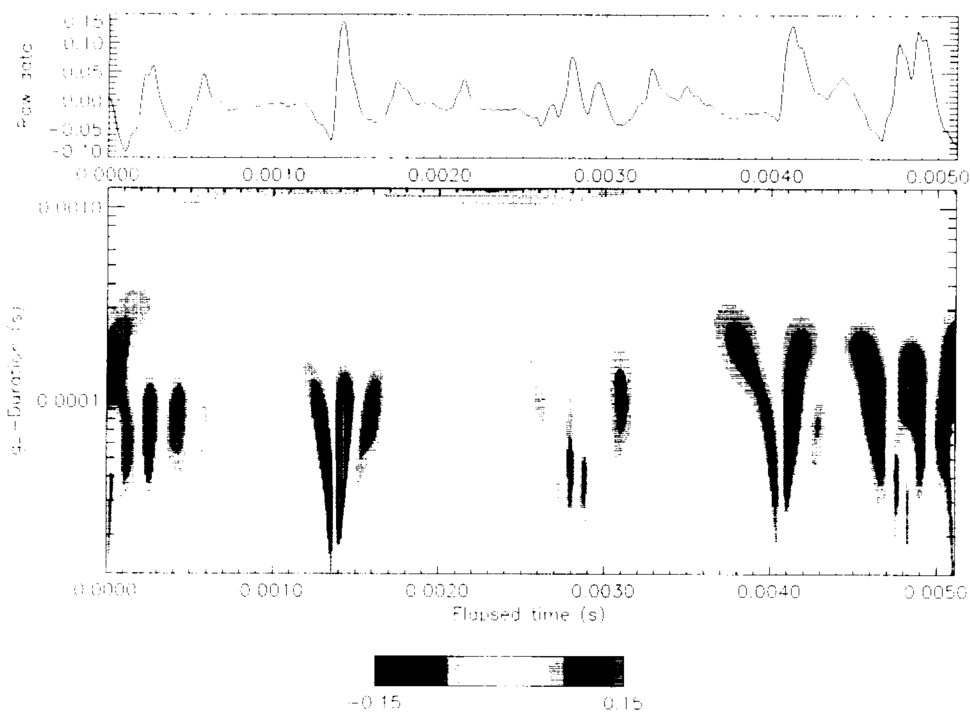

Figure 3: *Result of large-event removal on the same sample shown on Fig 1. The wavelet coefficients of the small superposed events are modified.*

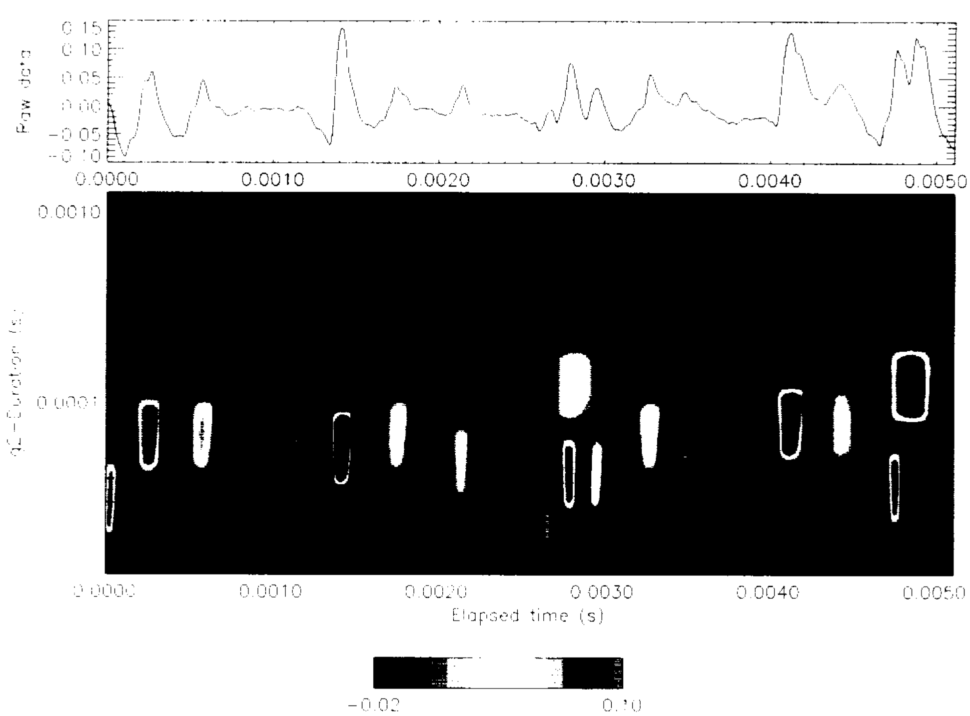

Figure 4: *Result of large-event removal on the same sample shown on Fig 2.*

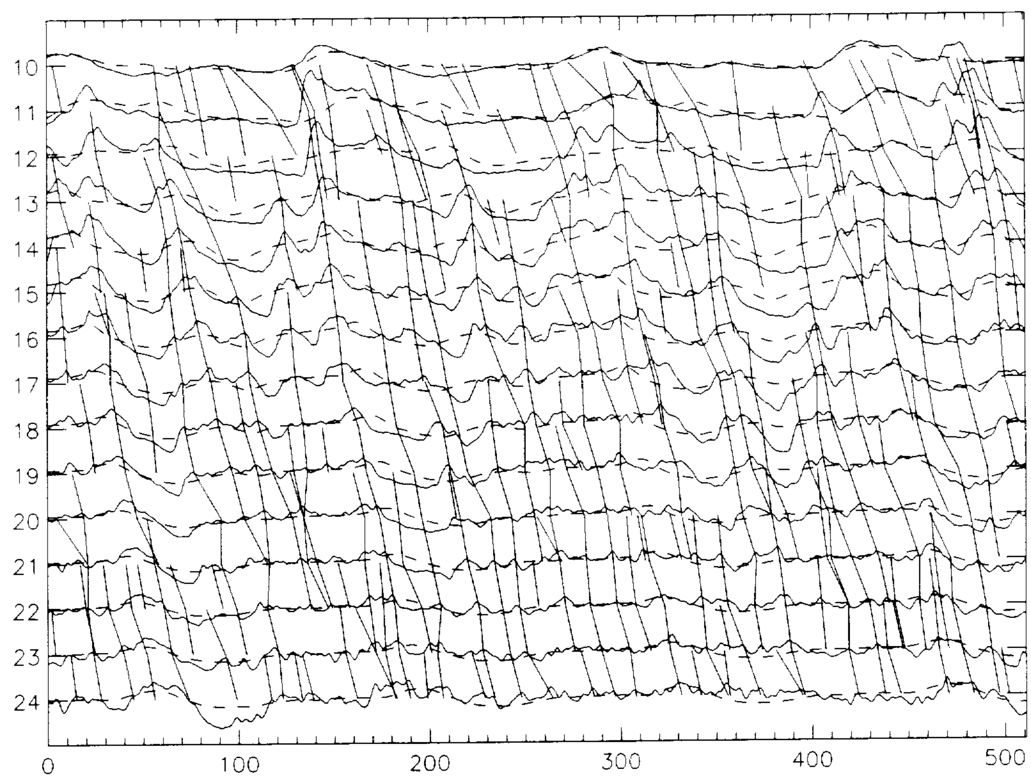

Figure 5: *One sample of simultaneous traces (horizontal solid lines) from the beginning of transition (station 10) to the trailing edge (station 24). Events are traced from station to station. Ensemble mean is shown in dashed lines. Abscissa shows 512 successive samples, ordinate is PWSS in arbitrary units.*

On Fig. 5, the stations are labeled from 10 (beginning of transition) to 24 (trailing edge) in the streamwise direction, following the notations of Halstead et al. [6]. The four major 'events' at station 10 are interpreted as the wake passings. The excerpt used for illustrations on Figs. 1 to 4 appears at station 12. The gradual increase in the number of smaller scale events is consistent with the development of turbulence along the blade surface. Convection of the events along the blade surface is reflected in the slope of their trajectories on the plot.

Some of the details, however, are not quite right. For example, between traces 14 and 15 at t = 400 units, the algorithm chooses a fairly slanted trajectory (low convection velocity) as a better match than the obvious rise leading up to the peak. This is caused by the lack of shape characterization (pattern recognition) in our algorithm, and possibly by the next-trace matching as opposed to a multiple trace matching. Improvements in this regard will be discussed in Section 4.

3 Spot properties and their evolution

The events analyzed below were extracted from the Halstead data [6], using the first 512 points from each record. The events, presumably spots, can be followed between successive traces and can be assigned some quantitative properties. Not all properties are equally accurate, as pointed out for each item in the list:

1. Time of occurence: some arbitrariness in selecting a maximum (on time traces) or peak of wavelet transform; alternatives include a center-of-mass or other weighted local moment of the signal.

2. Phase angle relative to the wake passing at each location; this is based on ensemble averages traces, and is accurate.

3. Chord value: as provided.

4. Dominant frequency: the scale corresponding to the peak value of wavelet spectral energy density. This could be affected by the grazing[2] overlap of the (assumed) arrowhead shape of a spot on each sensor.

5. Energy density: here also, grazing overlap would affect the measured energy content.

6. Age: we only know when the structure starts showing on the traces, it could preexist and have grazing contact with the sensor.

[2]By grazing, we mean that the center of the spot being aligned randomly relative to the center and edges of the sensor can result in partial overlap.

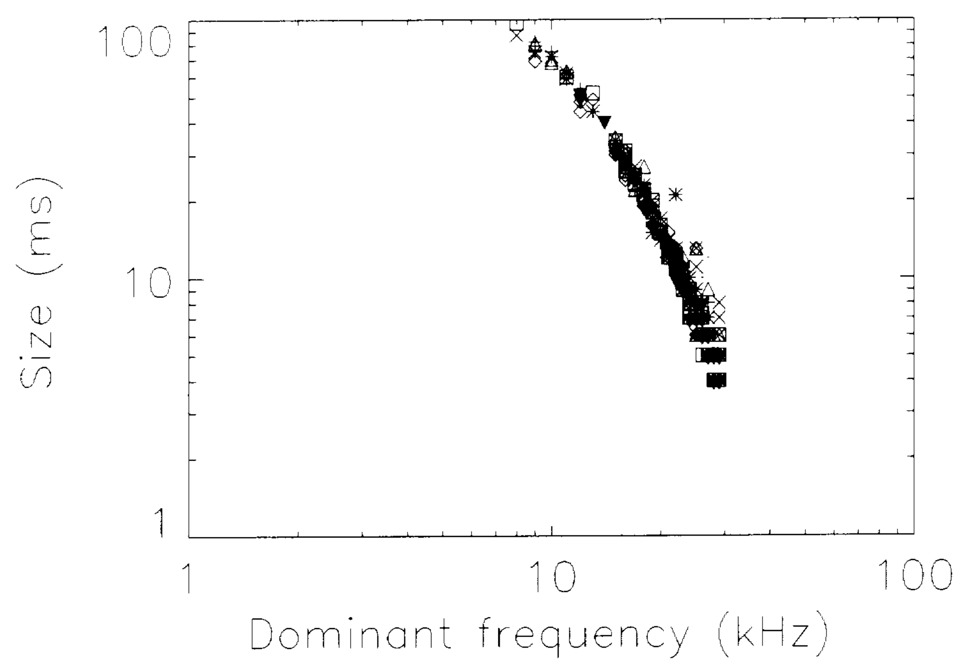

Figure 6: *Relation between spot size (time interval between leading and trailing edge, as estimated from wavelet maps) and dominant frequency. Different symbols identify successive stations (see Fig. 7 caption).*

7. Convection speed: by associating spot centers at successive chord locations, we can obtain their convection speeds from the time lag from sensor to sensor. This depends on correct times of occurence as well as trace-to-trace matching.

8. Leading and trailing edge locations: somewhat arbitrary, we look for change of sign in the wavelet map at the dominant frequency. Frequency resolution of the data does not allow a precise determination except for a few 'nice' spots.

9. Size: time difference between leading and trailing edge, it may be biased to low values because of grazing incidence on the sensor. It should be related to the frequency through the covnection speed.

10. Leading and traling edge convection speeds are easy to obtain from the above, with the same uncertainties.

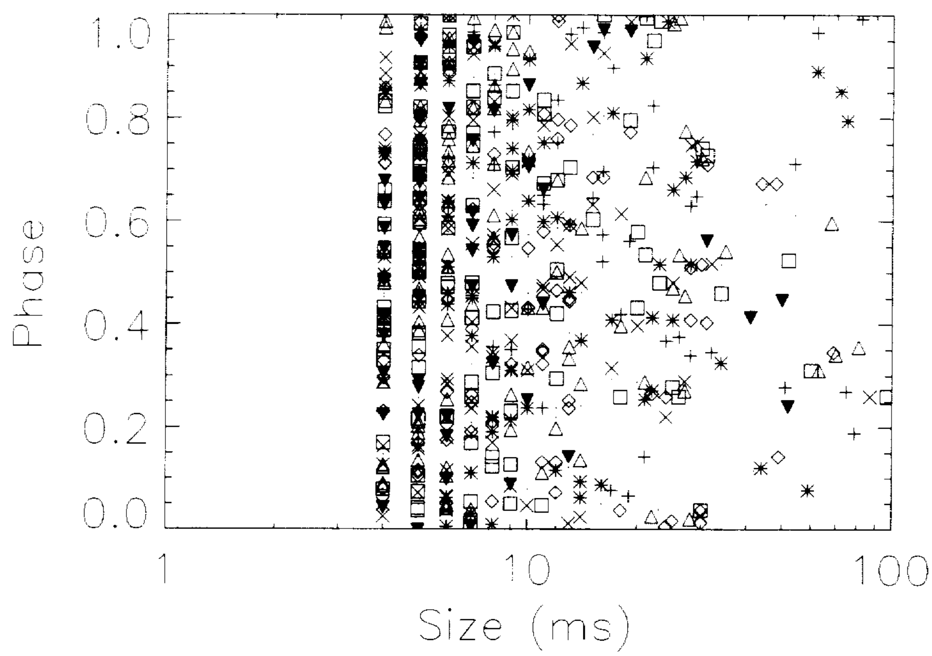

Figure 7: *Scatter plot of phase (relative to wake passing) versus spot size at successive stations. Symbols: + traces 8 and 9; * traces 10 and 11; · traces 12 and 13; ◇ traces 14 and 15; □ traces 16 and 17; △ traces 18 and 19; × traces 20 and 21; filled ∇ traces 22-24.*

Fig. 6 shows the relation between the spot size, as measured by the time interval between leading and trailing edge for each spot, and the frequency, measured by the peak frequency on the energy maps. The inverse proportionality (slope -1 on the log-log plot) appears to hold best for the largest spots, while the shorter ones exhibit a slope closer to -2. The lack of linearity is presumably associated with the inaccuracies associated with spots that cover only a few data points. Higher frequency resolution of the data might improve the results. The overall one-to-one relation between size and frequency over all stations is encouraging.

Fig. 7 shows that spot size seems independent of phase relative to wake passing. Furthermore, no pattern emerges that would relate spot size to chordwise location. This conflicts with the expectation of spot growth in the streamwise direction. A similar lack of trend was observed when spot dominant frequency was substituted for size. Two interpretations are possible. First, the accuracy of the size and frequency

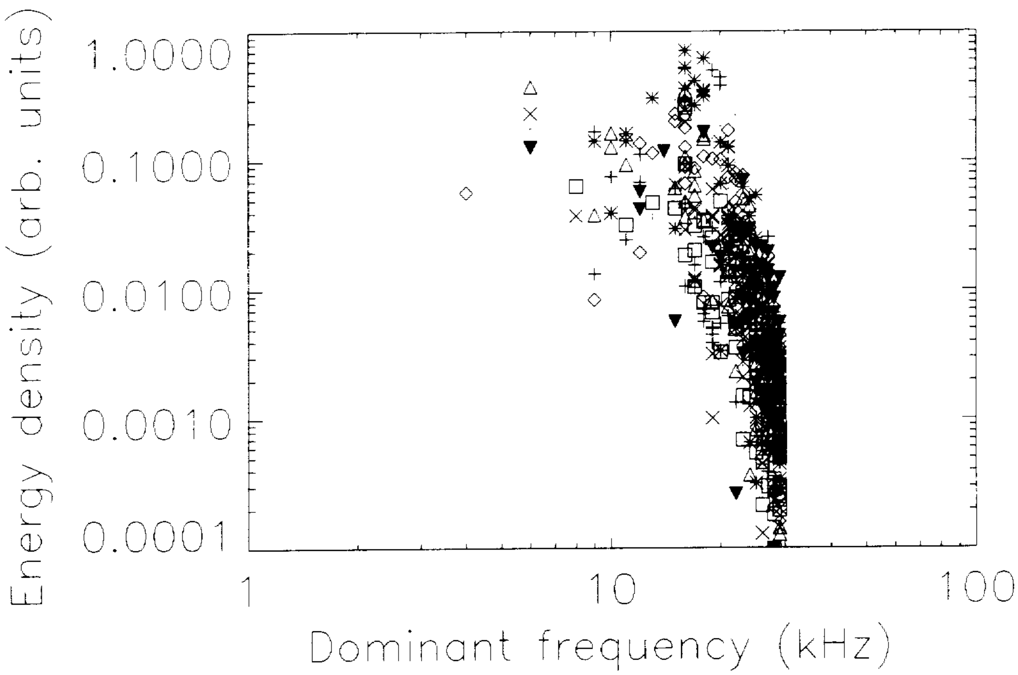

Figure 8: *Scatter plot of energy density vs. frequency. Symbols as for Fig. 7.*

parameters could be at fault, because of confounding effects of grazing overlap of the spot on the sensors, and/or because of frequency resolution effects. Alternatively, it is possible that crowding of spots in the rapidly evolving flow interferes with the determination of size.

Size, however, is not a meaningless parameter, as seen from Fig. 8. The scatter plot of energy density versus frequency reveals a few trends that might merit further scrutiny. For example, at the top of the plot, the most energetic events occur over a relatively small range of scales. Spots of median energy level occur over the widest range of scales, while the weakest spots are the smallest ones as well, and are associated with the earliest events. Since the energy measure is a *density*, this observation is not trivial. Further study might indicate if grazing incidence of spots on the sensors accounts for this correlation, or if a physical connection exists.

A different section through our parameter space is given by the plot of energy as function of phase relative to wake passing on Fig. 9. We see the most energetic events occuring in phase opposition to wake passings, and at the early stations in the transition process. This points to the largest spot energy densities being associated

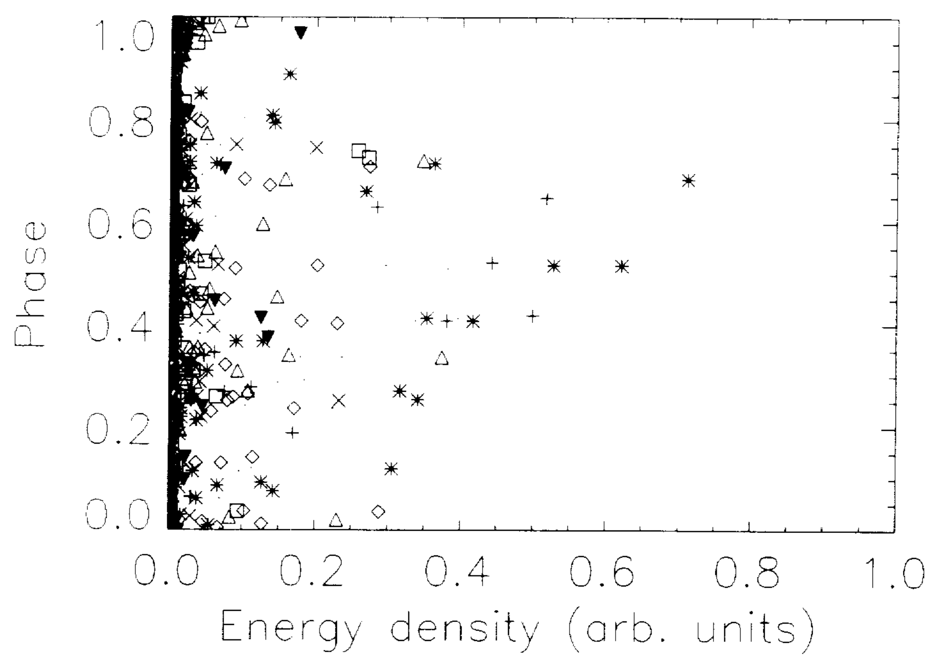

Figure 9: *Energy density as a function of phase relative to the wake passing. The strongest events are seen to be at a relative phase of approximately .5, i.e. to be located preferably between wakes. Also, these events occur in the transition. Symbols as for Fig. 7.*

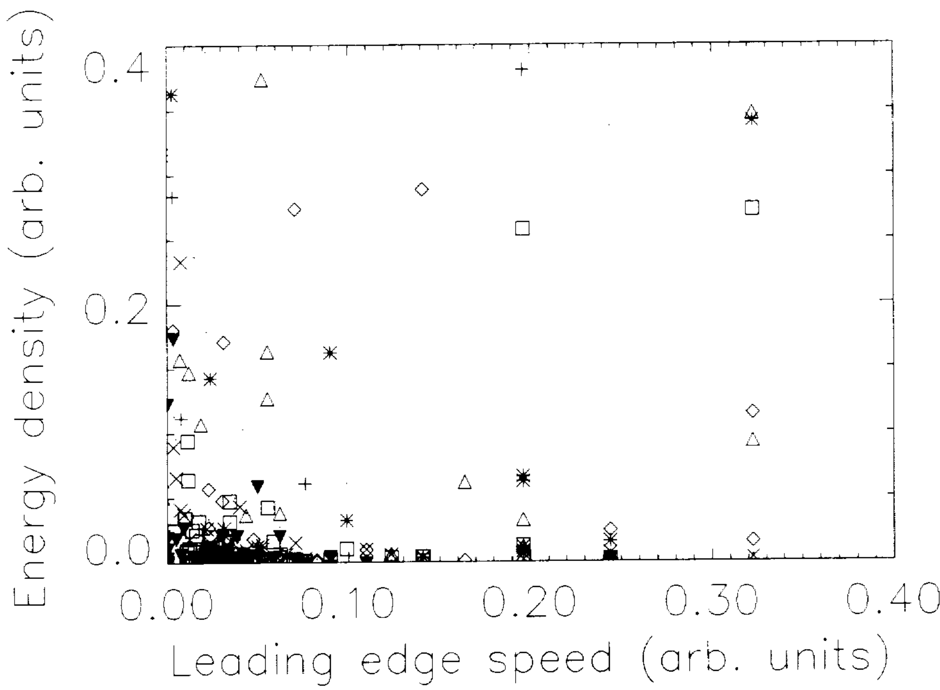

Figure 10: *Scatter plot of leading edge speed and energy density along the blade. Symbols as for Fig. 7.*

with natural, as opposed to wake-induced, transition. It is worth noting that grazing incidence does not overcome this trend, and that spot crowding (or lack thereof) seems to affect the energy density or its measurement.

In combination, these results show that spots with the largest energy density tend to occur in the absence of wake-induced disturbances, and they tend to be of moderate size. The bypass transition associated with wake passing and the downstream growth (and crowding) of spots as the transition process nears completion, do not favor large energy densities.

Other combinations of parameters showed no significant trends. They are worth reporting, since an absence of trend would allow for simpler models to be used. For example, on Fig. 10, the leading edge speed is plotted against the energy density. Similar results were obtained with spot center convection speed. The considerable scatter in speeds was already visible on Fig. 2.3. In contrast, Fig. 11 shows a wider range of scales for the slow-moving spots, and a narrow band of (small) spot sizes for the large speeds. This indicates that a lack of trends on other plots is not due to the

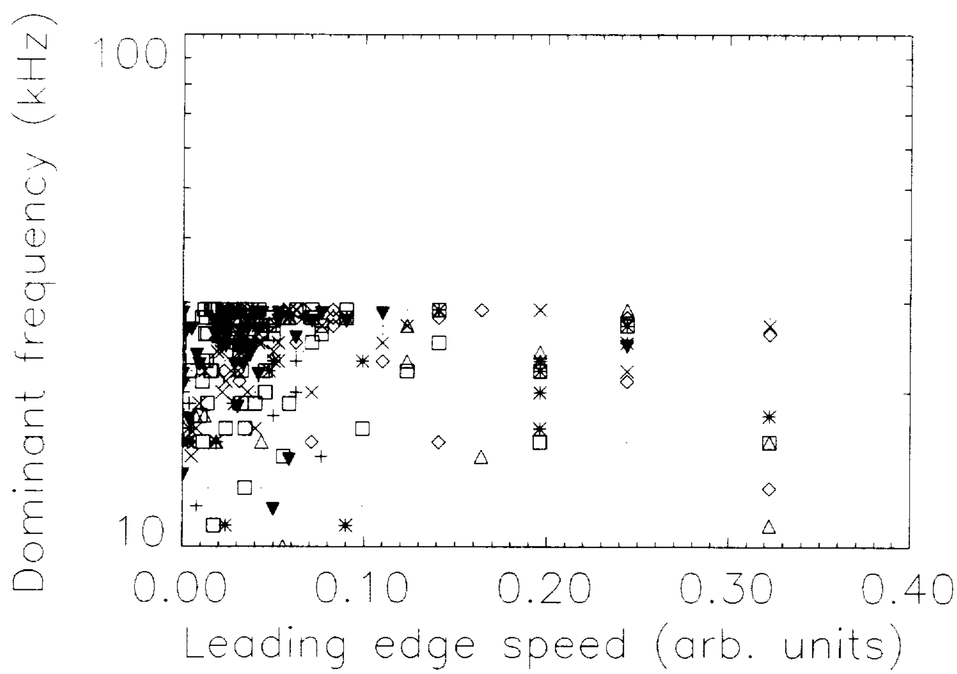

Figure 11: *Scatter plot of leading edge speed and frequency along the blade. Symbols as for Fig. 7.*

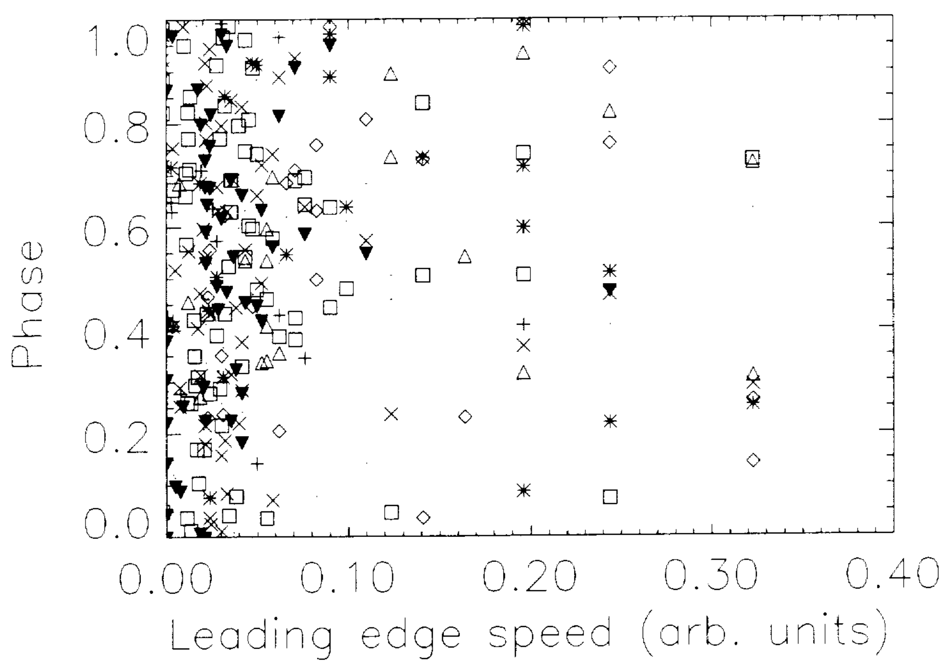

Figure 12: *Scatter plot of leading edge speed and phase relative to wake passing along the blade. Symbols as for Fig. 7.*

speed being a bad statistic. So, the observation on Fig. 12 that spot speed is not strongly phase dependent is potentially useful for modeling purposes.

4 Discussion

The GEAE database on unsteady transition was used in the evaluation of spot characterization. This study aimed at the evaluation of techniques for measuring spot properties, at preliminary assessment of which properties appear sensitive or insensitive to wake-induced or natural transition, and at recommendations for further data collection aimed specifically at the collection of data for modeling spot properties in turbomachinery.

The main findings are that four spot properties of modeling interest have been quantified: frequency, energy, convection speed and phase. The correlation between energy density and phase (Fig. 9) maybe counter-intuitive, since the most energetic events occur between wakes. Although this observation is subject to interpretation (below), its confirmation would affect modeling requirements in unsteady transition. The energy density is also correlated to spot size (Fig. 8), but size and phase do not seem to be correlated (Fig. 7). When convection speed is concerned, no correlations were apparent.

The measurement of spot properties is conditioned by the naturally unpredictable location of spots relative to the sensors. A systematic documentation of the effect of grazing or head-on overlap of individual spots and sensors would provide a measure of the magnitude of this effect. Given this uncertainty, we were able to assign a number of quantitative properties to the events. The representation of individual traces in the time-frequency domain enabled us to isolate individual events, and to remove the effect of large-scale energetic neighbors from the measured properties. The most significant improvements would result from improved event tracking, resulting in more reliable convection speeds. Current tracking is based on matching an event in a given trace with the best possible candidate at the following station. Visual examination shows that, while the algorithm is generally satisfactory, it might benefit from two-directional matching over more than two stations.

While improved algorithms (above) and dedicated data collection (below) would yield better quantitative results, a preliminary assessment is possible about the effect of wake passing on spot properties. A lack of effect makes the modeler's job easier, and this seems to be case for spot convection speed. However, some caution is necessary because convection speed is affected by both the tracking algorithm and the frequency resolution of the data. Also preliminary, but with consequences on modeling needs, is the variability in energy density and spot size with phase and chordwise location. These effects seems weakly correlated, in spite of the confounding effect of grazing spot incidence. Both effects could be related to spot crowding as the transition progresses.

The database used in this project is extremely rich in information, and was not assembled to study the details of spot motion. Higher frequency resolution would have several beneficial consequences: insight into the internal structure of events, with the possible distinction of spots and other disturbances, and improved location of the spots leading edges, would directly improve the current results. Also, the use of multiple miniature sensor arrays would provide useful information about the relative location of spots and sensors, and ensuing distortions of the spot's footprint.

In conclusion, this study points to future work related to spot characterization in turbomachinery flows. Feasible improvements to the data acquisition and the processing algorithms would lead to a more reliable and quantitative evaluation of modeling expectations in these complex flows.

References

[1] J.S. Bendat and A.G. Piersol (1993), 'Engineering applications of correlation and spectral analysis', John Wiley & Sons,

[2] J.P. Clark, T.V. Jones and J.E. LaGraff (1994), 'On the propagation of naturally-occurring turbulent spots', J. Eng. Math. **28**, 1-19.

[3] I. Daubechies (1992), 'Ten Lectures on Wavelets', S.I.A.M.

[4] M. Farge (1992), 'Wavelet Transforms and their Applications to Turbulence', Annual Reviews of Fluid Mechanics **24**, 395-457.

[5] D.E. Halstead (1996), 'Boundary layer development in multi-stage low pressure turbines', PhD Thesis, Iowa State University.

[6] D.E. Halstead, D.C. Wisler, T.H. Okiishi, G.J. Walker, H.P. Hodson and H.-W. Shin (1997), Boudary layer development in axial compressors and turbines, Parts 1-4 (ASME Papers 95-GT-461/462/463/464), ASME J. Turbomachinery **119**, 114-127, 128-139, 225-237 and 426-444.

[7] T.B. Hedley and J.F. Keffer (1974), 'Turbulent/non-turbulent decisions in an intermittent flow', J. Fluid Mech. **64**, 625-644.

[8] J.E. LaGraff, D.A. Ashworth and D.L. Schultz (1989), 'Measurements and modeling of the gas turbine blade transition process as disturbed by wakes', ASME J. Turbomachinery **111**, 315-322.

[9] J. Lewalle (1998), 'Applications of continuous wavelets to data analysis', Von Kàrmàn Institute Lecture Series on Advanced Measurement Techniques (VKI LS 1998-06, F.A.E. Breugelmans Ed.), Parts I, II and III.

[10] J. Lewalle, D.E. Ashpis and K.-H. Sohn (1997), 'Demonstration of wavelet techniques in the spectral analysis of bypass transition data', NASA TP-3555.

[11] J. Lewalle, D.E. Ashpis, D.E. Halstead and D.C. Wisler, (2000), 'The estimation of integral time scales in unsteady flows.', NASA TM-2000-209452.

[12] Y. Meyer (1993), 'Wavelets: algorithms and applications', S.I.A.M.

[13] C.W. Van Atta and K.N. Helland (1980), 'Exploratory temperature tagging measurements of turbulent spots in a heated laminar boundary layer', J. Fluid Mech. **100**, 243-255.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	December 2000	Final Contractor Report

4. TITLE AND SUBTITLE

Detection, Tracking and Analysis of Turbulent Spots and Other Coherent Structures in Unsteady Transition

5. FUNDING NUMBERS

WU-523-26-33-00
C-76220-D

6. AUTHOR(S)

Jacques Lewalle

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Syracuse University
Department of Mechanical, Aerospace and Manufacturing Engineering
Syracuse, New York 13244

8. PERFORMING ORGANIZATION REPORT NUMBER

E-12622

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA CR—2000-210694

11. SUPPLEMENTARY NOTES

Project Manager, David Ashpis, Turbomachinery and Propulsion Systems Division, NASA Glenn Research Center, organization code 5820, 216-433-8317.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified - Unlimited
Subject Categories: 34, 02, and 07 Distribution: Nonstandard

Available electronically at http://gltrs.grc.nasa.gov/GLTRS

This publication is available from the NASA Center for AeroSpace Information, 301-621-0390.

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

Transition on turbine blades is an important factor in the determination of eventual flow separation and engine performance. The phenomenon is strongly affected by unsteady flow conditions (wake passing). It is likely that some physics of unsteadiness should be included in advanced models, but it is unclear which properties would best embody this information. In this paper, we use a GEAE experimental database in unsteady transition to test some tools of spot identification, tracking and characterization. In this preliminary study, we identify some parameters that appear to be insensitive to wake passing effects, such as convection speed, and others more likely to require unsteady modeling. The main findings are that wavelet duration can be used as a measure of spot size, and that spot energy density is most closely correlated to the wake passing. The energy density is also correlated to spot size, but spot size appears unrelated to the phase angle. Recommendations are made for further study.

14. SUBJECT TERMS

Turbulence; Transition; Turbomachinery; Unsteady flows; Boundary layers; Turbulent spots; Wavelets; Wakes; Freestream turbulence; Coherent structures

15. NUMBER OF PAGES

25

16. PRICE CODE

A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	